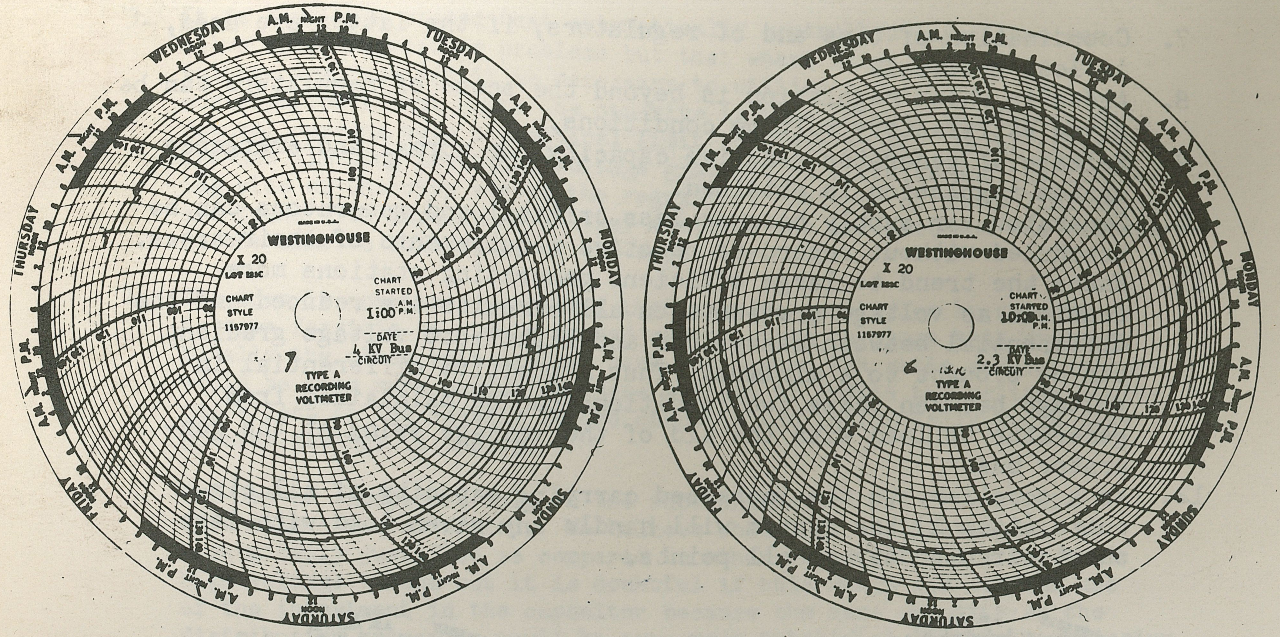
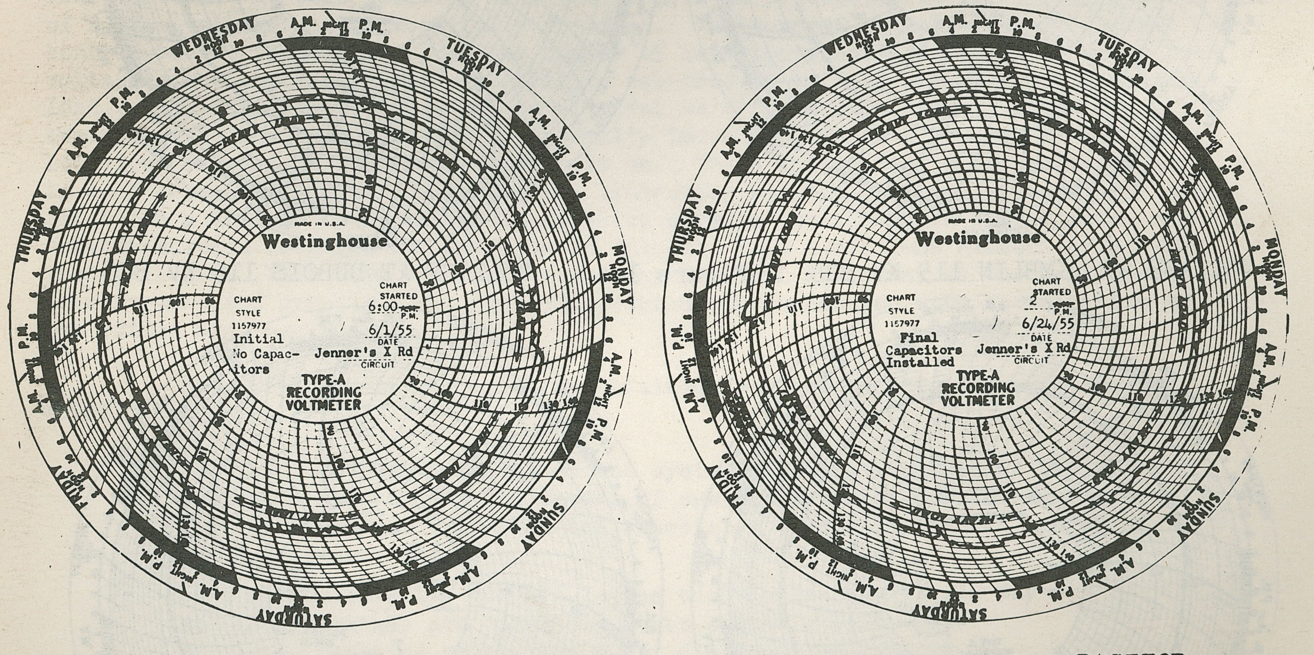


VOLTAGE AT BROOKVILLE 4 KV BUS   Figure 1-c   VOLTAGE AT BRADY ST. 2.3 KV BUS



INITIAL VOLTAGE AT CAPACITOR STATION ON RURAL CIRCUIT PRIOR TO INSTALLATION OF CURRENT-VOLTAGE CONTROLLED CAPACITORS   Figure 2   FINAL VOLTAGE AT CAPACITOR STATION ON RURAL CIRCUIT AFTER INSTALLATION OF CURRENT-VOLTAGE CONTROLLED CAPACITORS

Transactions Paper

(Reviewed and Accepted for Publication)

PENNSYLVANIA ELECTRIC COMPANY'S CAPACITOR PROGRAM

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In order that the reasons for the development of Penelec's capacitor program and its type of capacitor control may be more clearly understood, a brief resume of the situation existing at the time it was initiated may be in order.

Conditions Leading to Adoption of Program

During the period of rapid load increase after World War II many circuits had reached a point where the regulation had become critical and it was apparent that with a further slight increase in system load the installation of many regulators and many new circuits at all voltage levels would be required. Prior to this time a policy of swinging the voltage at the generator busses had been initiated but it applied to only a few stations and amounted to only two or three percent. It had been initiated largely because of high light load voltages experienced at distant unregulated substations. No actual schedule was used and it was mostly done at the discretion of the dispatcher, so more often than not it was used to correct some local voltage condition rather than for the general benefit of the system. Nevertheless it had done some good, because aside from lowering off peak voltages it became practical to cut out of service all of the regulators in the city of Johnstown.

The first step considered then to improve system regulation was to increase the voltage swing at the generator bus and to schedule it as a function of variation in system load. This voltage swing was increased to 8% and when put into effect it greatly improved regulation at all points on the system. Locations electrically close to the generator bus had a rising voltage characteristic as system load increased and locations electrically distant had much less normal regulation than formerly. The maximum increase in voltage at heavy load over light load on the transmission system was less than 4% while at nearly all locations the transmission system had at least some rise at heavy load.

This voltage swing was beneficial to the system and few customers experienced any large portion of the voltage rise caused by the voltage swing because of the "ironing out" effect of system impedances, particularly the transformers. In some instances where a distribution system was fed directly from the generator bus, the voltage of the circuit at its source would, of course, vary the full 8%. This was not entirely unfavorable because, in most instances, the rise was little more than would have been occasioned by a current compensated regulator on the circuit.

At the time this scheduled voltage swing was being put into effect the matter of a capacitor program was being considered for the system. It was necessary that capacitors be disconnected from the system at light load because many generating stations were operating at a very high power factor during this period. This resulted from the leading reactive contribution of the comparatively great total length of transmission circuits in the system. Voltage control of the capacitors was considered but it was obvious that with the system voltage rising with load, which we felt was highly desirable, the voltage control would bring the capacitors on at light load and take them off at heavy load in many instances. Other conventional methods of control were considered but were found unsatisfactory because it was obvious that they would

often take the capacitors on or off at undesirable times. Also in studying the problem it was beginning to be realized that in addition to obtaining the conventional benefits from capacitors it would be possible and highly desirable for them to take over the major role in regulating local and system voltage. When a comparatively inexpensive and reliable tool in the form of capacitors was available to offset the lagging reactive component, and thereby improve voltage at the load and throughout the system, it seemed desirable to discontinue the past practice of raising voltage at a circuit source to force this component through expensive circuits.

Development of Current-Voltage Capacitor Control

Therefore, in order to take full advantage of the possibilities in the capacitor, it was decided that a new type of control should be devised. This control would have to work well with the system voltage level rising with load (this characteristic can be created either by voltage swing at the generator bus or by the capacitors themselves or by the combination of both), and voltage should still be the criterion for its operation if regulation of voltage was to be a principal function of the capacitor. This led to the development of the current compensated voltage capacitor control in which the function of the current element is simply to vary the voltage range of the control in accordance with the change in load at its location. During the light load period the capacitor will be on or off within a certain voltage range and during the full load period it will be on or off within a certain higher voltage range.

There are several variations of this type of control in service. It consists essentially of a standard voltage control device with either a current bias on the master relay element produced by the secondary of a current transformer in one leg of the three phase circuit or by a current relay actuated by the secondary of the current transformer to shunt out, below predetermined current values, a variable resistor in series with the potential coil actuating the master relay. In either case the load current acts to raise the operating voltage level required to operate the master relay as load increases, but does not change the predetermined operating band width. The band width and the change in operating level of voltage to actuate the control system can each be adjusted to suit the conditions at each capacitor location.

Results of the Capacitor Program

The application of capacitors with this type of control to the distribution system has been very advantageous to the entire system. Calculating board studies made at the time the capacitor program was initiated indicated that with automatically controlled capacitors on the distribution circuits, system loads could be doubled without additional transmission or subtransmission circuits being required, while on the other hand if voltage regulation were to be offset by regulators many new circuits of all types would be required even though the voltage swing at the generator bus were to be continued. The results of this study have been confirmed by experience in that voltage regulation is held within reasonable limits by the capacitors. Of course new circuits have been built but these are mostly in conjunction with a new generating station or specific large new loads. On the other hand several generating stations have since that time been removed from normal operation and the regulation in their areas has been well handled by the capacitors on the distribution system. Also a number of circuits have been re-conductored. This would not likely have been practical without the capacitor program as the voltage improvement would have been too insignificant.

We have had enough experience with this type of capacitor control to be certain that as the system loads increase, circuits in all categories can be made to take their full economic load before it is necessary to supplement them because of voltage regulation. Also, the entire system can have a rising voltage characteristic with increasing load as far as the last load center on each primary circuit no matter how far it may be from the generating station.

Those who have been connected with this program and who have studied it are convinced that the application of capacitors with this type of control to the system eliminates the need for regulators in most cases and will give better voltage control at all points on the system with less voltage gradient throughout the system than can be obtained with conventional types of regulation. It is further believed that most of the capacitors installed should be put under control to contribute their potential effect to regulating system voltage.

Discussion of Benefits

In most conventional analyses of the economics of distribution capacitors vs. regulators little consideration is given to the integrated effect of distribution capacitors on the transmission and subtransmission systems. In some areas on the subtransmission system the combined effect of generator bus voltage swing and the distribution capacitors raises the voltage level over 20% above that which would otherwise be experienced at heavy load. In addition to this the average rise at the primary circuit load centers from the high side of the distribution substation transformer may be in the order of 8% as a result of the integrated effect of all capacitors on circuits from that substation. The combined rise that would have to be handled by regulators if they were to be substituted for generator bus voltage swing and capacitors is therefore 28% or more. It is evident that regulators on the substation bus could not handle required rises of this order and that if they were relied upon to take care of regulation in these areas much more circuit capacity would be required. Since present circuits are not loaded to economic capacity, in effect, these new circuits would be constructed to carry reactive component. This is a costly method of handling var load and voltage regulation when it can be offset by automatically controlled capacitors at about $10 a kvar. This is particularly true when it is considered that the entire cost of the capacitor and its maintenance is more than offset by loss savings alone.

In order to demonstrate the quality of voltage regulation obtained by these means Figures 1-a and 1-b show respectively a weekly chart of voltage on the high and low side of two transmission substations which are fed from long heavily loaded transmission circuits having considerable variation in loading resulting from economic scheduling of generating stations. The voltage swing created by the swing at the generator bus is quite pronounced on the 115 KV side. It should be noted, however, that on the low voltage side because of the influence of the variation in reactive component of the load and the transformer reactance the variation in voltage is considerably less. Figure 1-c shows weekly voltage charts of two distribution substations which are located on a long heavily loaded (for its length) subtransmission circuit between the above two transmission substations. One distribution substation, Brookville, is about midway on the subtransmission circuit. The other, Brady Street, is quite close to one end near the Dubois transmission substation.

Both distribution substations have automatically controlled capacitors on their busses. This is not advocated except under certain conditions. The voltage steps in the order of 2% resulting from these capacitors may be noted on the Brookville chart. However the voltage at both these busses is mostly influenced by other capacitors in the area.

Figure 2 shows voltage at a capacitor station before and after the application of capacitors on a long rural circuit.

It may be well here to discuss, in the light of Penelec's experience with their capacitor program, some of the objections often voiced to the use of capacitors for voltage control and the restraints often suggested as necessary for their economical use. This discussion follows:

1. It is often stated that voltage regulation by capacitors is coarse as compared to the fine regulation obtained by regulators. It is quite true that Penelec uses capacitors on some distribution circuits that increase voltage at the capacitor location by as much as four percent per step. However on such circuits the normal voltage dips caused by motor starting, etc. are of much the same order. The amount of rise from the capacitor can, of course, be controlled by its size and location. The size of this step does not mean however that when compared with regulators the voltage regulation is coarse, because at the substation where the regulator would produce its stepped voltage rise, the rise from this capacitor is usually only a fraction of the 4%. The portion of the rise at the bus occasioned by other capacitors on the system along with the voltage swing at the generator bus is added in small increments which in total can amount to ten or twenty percent or even more at heavy load. These increments of voltage change at the bus are smaller than would be obtained by any type of regulator on the bus.

2. A number of articles have recently been published to the effect that regulation of voltage by capacitors is more economical than by regulators only under certain conditions. A variation of this is to the effect that a combination of the two methods is the most economical. These analyses in effect balance one regulator installation against a single capacitor installation. Thereby they fail to recognize the basic difference in the two methods. Each capacitor installation on a system aids and integrates its effect with every other capacitor; thus most of the voltage rise created at a given point may come from capacitors other than the one applied at that location. The effect of regulators is exactly opposite. <u>As each one attempts to raise voltage in the distribution system it tends to lower voltage on the source side.</u> In fact when a number are paralleled from a high voltage circuit the net effect may simply be a reduction of voltage on the high voltage circuit. Thus regulators cannot be effective in holding voltage beyond a certain limited reactive flow. If sufficient leading reactive is supplied in the area to make the regulators completely effective the capacitors can also do the regulating of voltage if put under control. The regulators, we believe are simply an unnecessary added expense that also create problems in operation because of problems in coordination that develop on a complicated system.

3. It is sometimes stated that automatically controlled capacitors can solve minor regulating problems but that where large variations in voltage are required it is necessary to utilize regulators. It is our experience that quite the opposite is true because regulators for several reasons have a practical limit to their range. Among these are the limiting practical voltage gradient on circuits and the limiting size of the step across the regulator. Neither of these limitations are found with capacitors as they minimize the gradient and the voltage is the same on both sides of the capacitor.

4. The idea is sometimes expressed that voltage regulation by capacitors is more feasible on widely spread systems than on close knit systems. Usually the close knit systems have the higher X/R ratio and capacitors would be even more useful on these systems to reduce the voltage limiting effect on the heavily loaded circuits and incidentally would make greater savings in losses.

5. The use of capacitors only on the subtransmission and transmission system is often advocated. We believe that this application may be economically justified as compared to other means of regulating the high voltage system but it is doubtful if this makes the maximum use of the investment in the capacitor because the same quantity on the distribution primaries would be even more beneficial to the transmission system by the amount of I^2X losses saved and would play a part in regulating voltage at the distribution load centers as well as saving I^2R losses on the distribution system. At the same time the capacitors located on the distribution circuits will greatly expand the possible loading and length of the circuits.

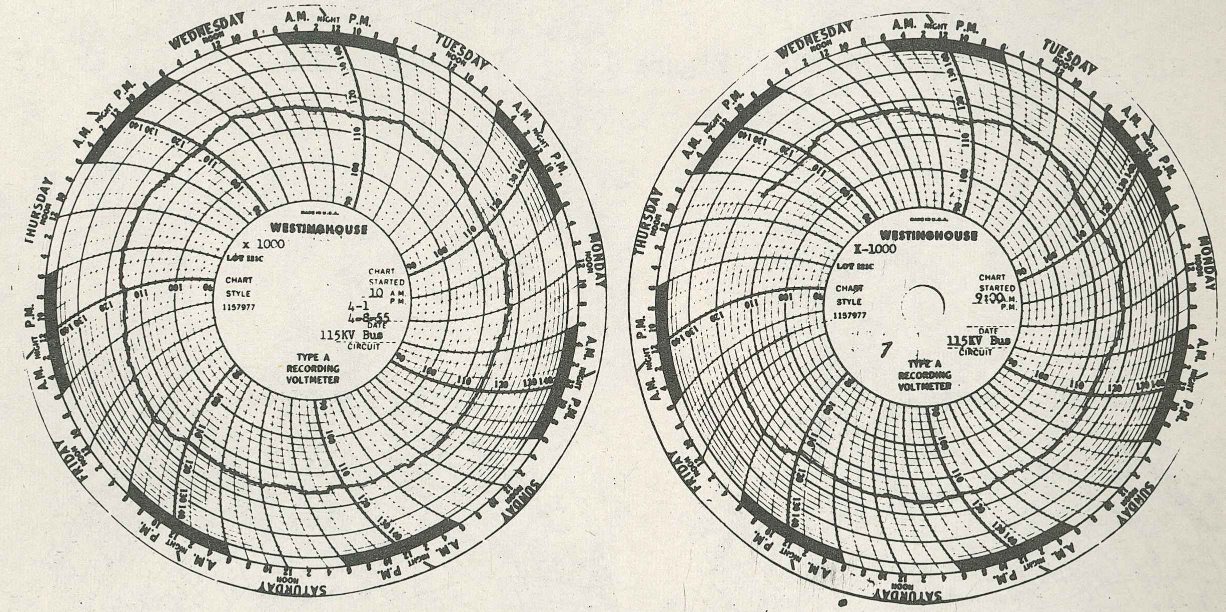
Conclusion

In conclusion, it may be said that for maximum use, the capacitor should be placed as far out on the system as possible, that is, at the distribution circuit load centers. At this location also its tremendous possibilities for the regulation of system voltage can be most fully realized. The current-voltage type of control contributes to this in that, as the number of capacitors increases and the heavy load voltage rises the capacitors can still be switched on at full load and off at light load. The control setting is not so critical as with voltage control alone and the average capacitor time in service is greatly increased. Also a voltage drop at its location need not be suffered to bring it on. These automatically controlled capacitors in each area, in conjunction with local generating stations (if any) feeding the area establish a voltage level at the loads which permits variations in transmission and subtransmission voltages to occur due to changing load conditions without affecting load voltages. This eliminates the necessity for TCUL equipment on the transmission transformers and greatly simplifies all problems in connection with coordination of tap ratios and regulators.

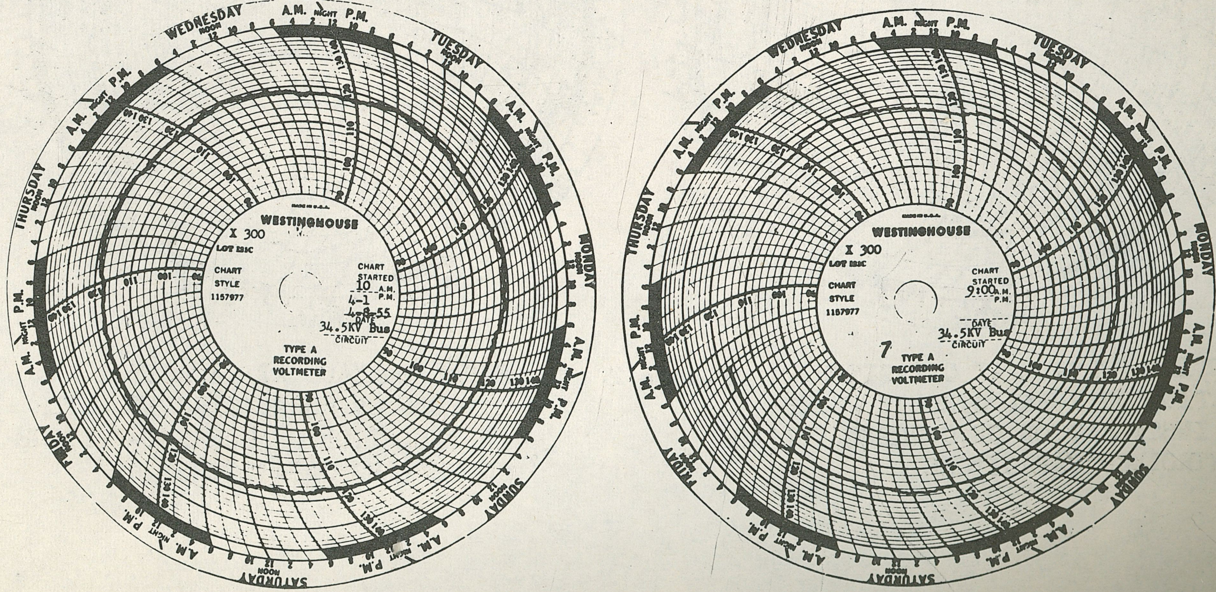
Some of the positive benefits obtained from the capacitor program may be briefly stated as follows:

1. The load carrying capacity of the system circuits has been at least doubled with a consequent saving of one-half present and future investment in circuits along with the associated saving in circuit operating and maintenance costs.
2. Saving in system I^2R and I^2X losses that incidentally will pay all fixed charges and operating costs of the capacitors.
3. Saving in required transmission and distribution reserve.
4. Distribution voltage conditions are more independent of transmission voltage conditions created by varying loads or outages than with regulators.
5. Longer circuits and heavier loads at any voltage are feasible. Therefore, substations of all types can be more widely spaced for any given system load.
6. Changes in circuit operating voltages will be delayed or made unnecessary.

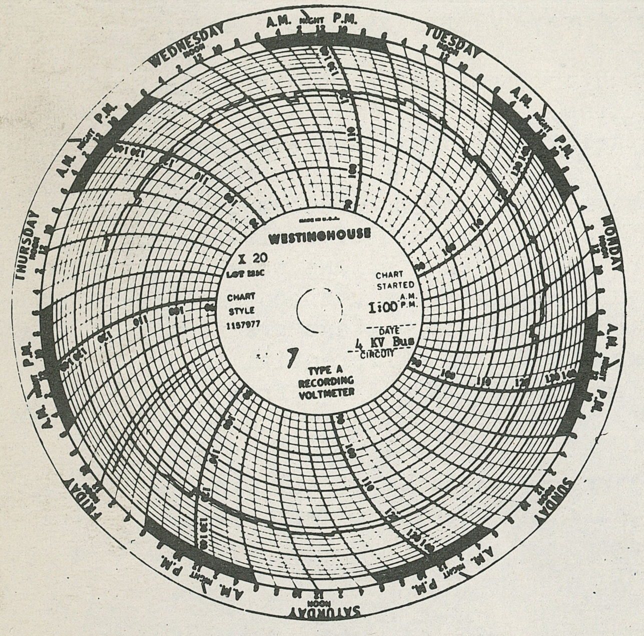
7. Coordination of taps and of regulators, if the latter are used, is less critical.
8. Areas in which regulation is beyond the scope of regulators can be given satisfactory voltage conditions.
9. Release of generator reactive capacity for normal and emergency system regulation is obtained.
10. Generator var supply becomes less critical and generators can be scheduled without regard to reactive requirements of their areas.
11. Makes the trend to large efficient generating stations more feasible as voltage gradients on all circuits are reduced and the differential between heavy load and light load voltage gradient can be brought to a minimum. Thus a positive differential in voltage between these two conditions can be maintained from generator to load with the aid of the voltage swing at the generator bus.
12. As a corollary to the increased carrying capacity of all circuits (item 1) the system will handle any given load with less short circuit duty at all points.



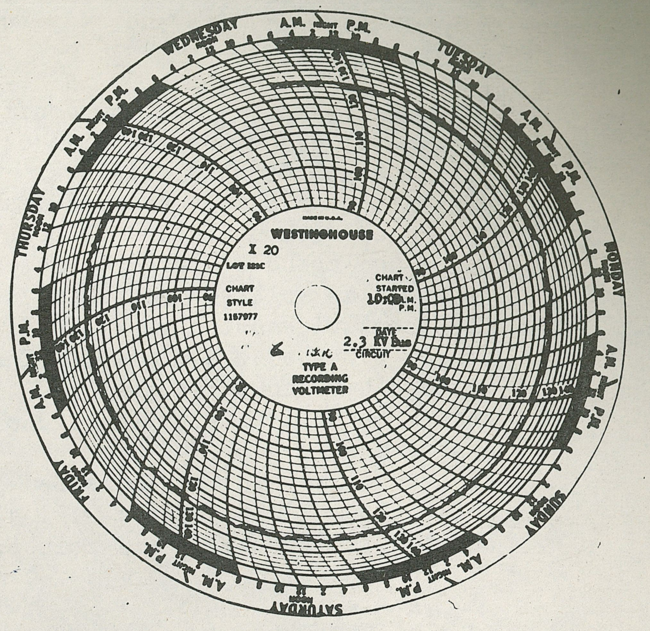
VOLTAGE AT TIMBLIN 115 KV BUS Figure 1-a VOLTAGE AT DUBOIS 115 KV BUS



VOLTAGE AT TIMBLIN 34.5 KV BUS Figure 1-b VOLTAGE AT DUBOIS 34.5 KV BUS

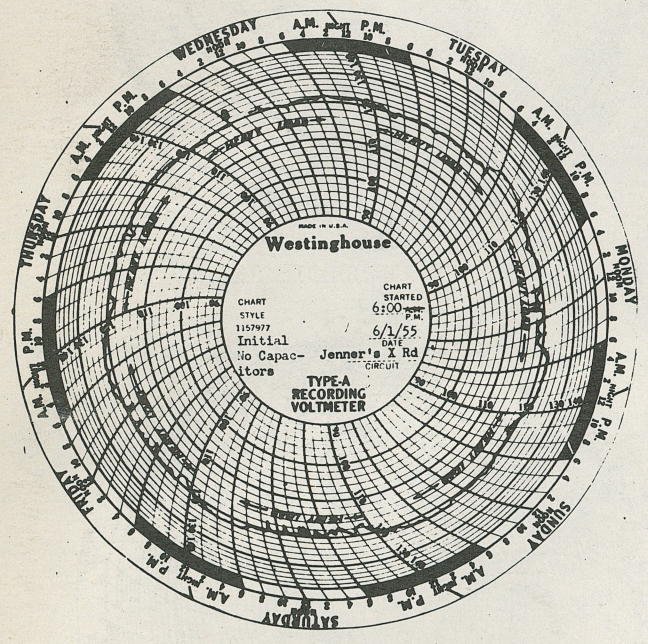


VOLTAGE AT BROOKVILLE 4 KV BUS

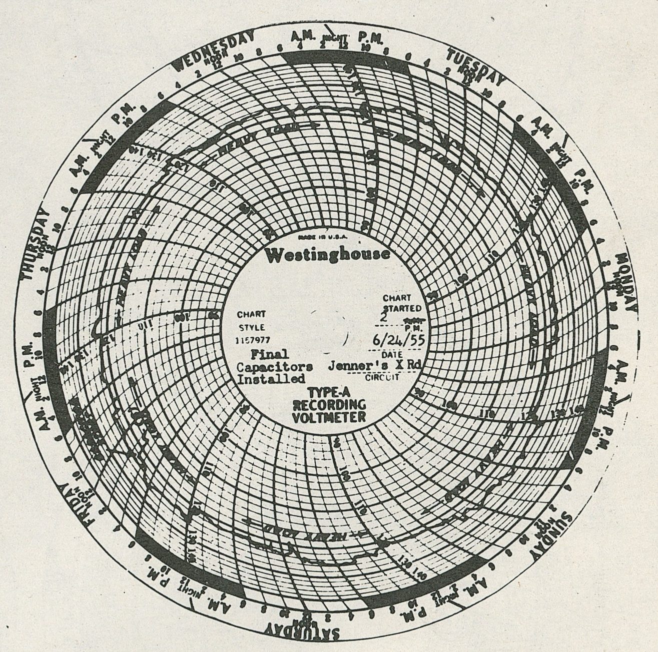


VOLTAGE AT BRADY ST. 2.3 KV BUS

Figure 1-c



INITIAL VOLTAGE AT CAPACITOR STATION ON RURAL CIRCUIT PRIOR TO INSTALLATION OF CURRENT-VOLTAGE CONTROLLED CAPACITORS



FINAL VOLTAGE AT CAPACITOR STATION ON RURAL CIRCUIT AFTER INSTALLATION OF CURRENT-VOLTAGE CONTROLLED CAPACITORS

Figure 2

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